The Moon as a Thanatocoenosis

IS THERE ANY HOPE FOR LUNAR PALEONTOLOGY?

P.J. Boston[1] and G.K. Schmidt[2]

[1]NASA Astrobiology Institute (NAI) penelope.j.boston@nasa.gov
[2]Solar System Exploration Virtual Institute (SSERVI) gregory.schmidt@nasa.gov
NASA Ames Research Center, Moffett Field, CA 94035.

R.D. Frederick, 2012

Biocoenosis = “Assemblage in Life”

Thanatocoenosis = “Assemblage in Death”

Taphocoenosis = “Assemblage after Deposition”

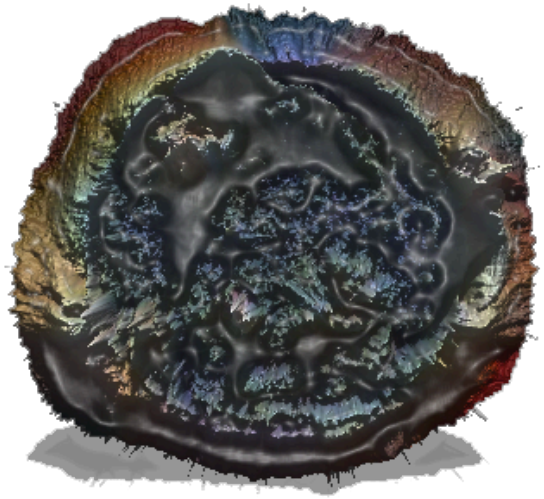
- An assemblage of fossil materials that exists in a particular deposit because they were transported there by some natural process, e.g. a river, a predator, wind… an Earth impactor (?)
- Time averaged assembly (poor temporal fidelity).
- Transported assemblage (poor spatial fidelity).

Ashfall Fossil Beds – Nebraska State Park


I can’t WAIT to achieve paleontological immortality on the Moon!
NASA/P.J.T. Leonard

Case Study – Putative Earth Material in Apollo 14 Sample

- Bellucci et al. 2019. *Earth Planet Sci Lett* 510:173-185.
- Possible Earth-derived material in lunar Breccia from Apollo 14 samples
- Age could be 3.9 to 4.0 BYA, dating evidence & argument is quite tortuous
- History of the object is highly complex (e.g. re-ejection at Imbrium)
- Significant secondary overprinting of lunar history onto an Earth specimen early in time



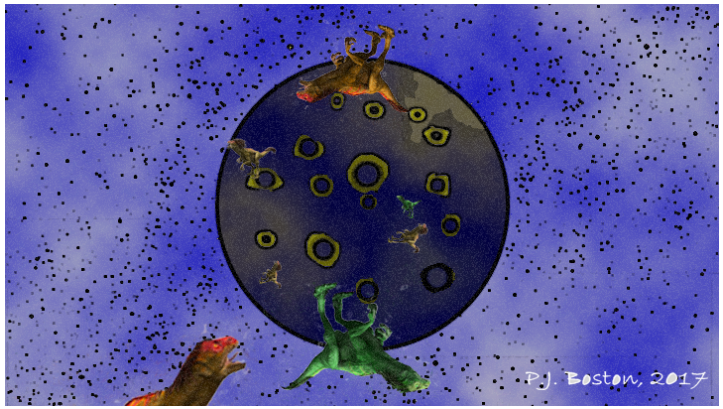
P.J. Boston, 2017

Ejection of Already Preserved Biological Material

- **Likely to be the most successful**
- Already subjected to preservation processes
- Already diagenetically altered in some cases
- Biomolecules trapped in various lithologies, e.g. hopanes & other lipids in chert
- Lithification via cementation, silica or carbonate
- Probably the only hope for body fossil fragments
- Biogeochemical traces

Ejection of Fresh Biological Material

- Case dependent, but….
- In general, likely to have a poor success rate for lunar persistence…
- However, transfer times much shorter to the Moon than to Mars.
- Could provide organic material with distinct Earth-like (i.e. biotic) stable isotopic ratios, even if degraded.
- Potentially *in situ* “mummified” remains of some biopolymers and even structures.
- Hard to interpret, of course.
- BUT….what about *“geogenetic latency”*



Question: How Much Biology Can Be "Stored" in Geology?

Preserved in a viable state in **sediments?**
Preserved in a viable state in **fluid inclusions?**
Preserved in a viable state at **great depths?**
Preserved in a viable state in **ices or salts?**

Hypothesis

Some tiny fraction of microorganisms survive burial and diagenesis, entombment in inclusions, etc.

Consequences for Earth

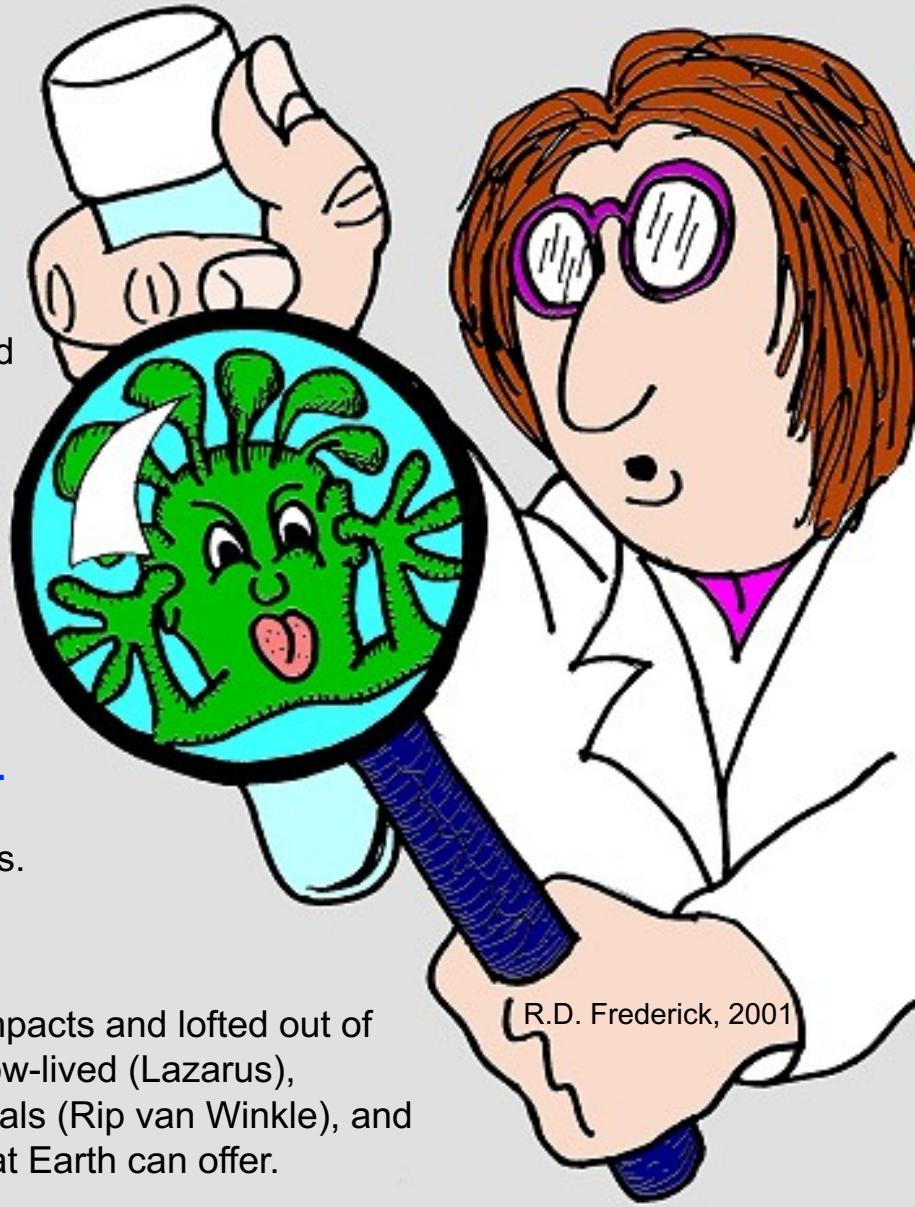
Lazarus, Rip Van Winkle, & Walking Dead organisms may provide a **"genome bank"** for Earth.

Deep, permanent indigenous subsurface microbiota re-exposed to the surface or ocean floor via geological processes, i.e. **"geogenetic latency".**

"Banked" genes (in viable orgs) reintroduced to the surface or ocean biosphere at geological intervals.

Panspermia Consequence

The most likely organisms to be excavated by major impacts and lofted out of Earth's gravity well, include those MOST long/slow-lived (Lazarus), capable of long-term viability in geological materials (Rip van Winkle), and hard to kill/destroy (Walking Dead) organisms that Earth can offer.



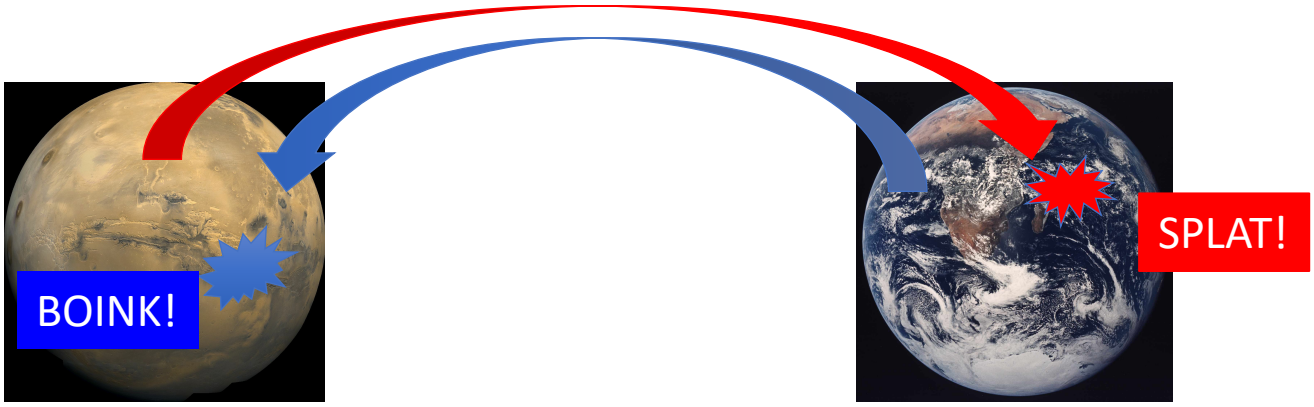
R.D. Frederick, 2001

Mars “Local” Panspermia & “Pre-prepared” Lunar Biosignatures

✧ ***Geogenetic latency*** on Earth driven by tectonics & other processes

✧ Microbial swapping from one planet to another?

- *Impact excavation of the geogenetic “bank”*
- *Tapping into populations that would be the MOST likely to survive this*
- ***Most likely to already be in a dormant and resistant state in rock***



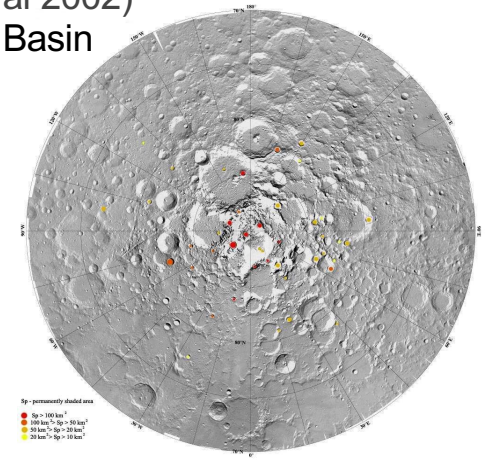
Spit-swapping Amongst The Rocky Terrestrials

Geogenetic latency on Earth & Mars, Boston et al 2009, 2012, 2019

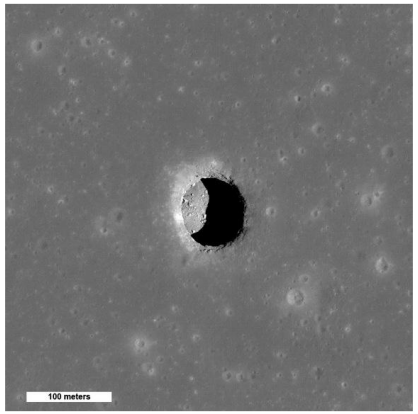
Where to Look

- **Ideally, low velocity impactors at high incident angle**
  - Lunar average impactor mass = 200 kg km^{-2} (*Armstrong et al 2002*)
  - 7ppm (*Armstrong et al 2002),* 1-2ppm (*Armstrong 2010*)
  - 50 W, 85S = 300-500 kg km^{-2} (*Armstrong 2010*)
    (8.4 X more impacts than the lunar average in Armstrong et al 2002)
  - Polar region impact mass, especially near South Pole – Aitken Basin

- **Permanently shadowed areas minimizes UV and solar particles**
  - Can act as collecting buckets
  - (*Shevchenko & Kozlova 2002*)
  - Water ice predictions, but could also protect & entomb



- **Cave entrances could serve as collection repositories and provide some protection**
  - *Boston 2004, Leveille & Datta 2010*, etc.
  - And they are super cool!
  - NIAC Phase 3 just awarded to Red Whittaker et al, Carnegie Mellon



Pit cave entrance
Mare Tranquilitatis

- **Protection from burial by lava, pyroclastic ashfall, etc.**
  - *Fagents et al 2010, Rumpf et al 2013*

Model-based maps

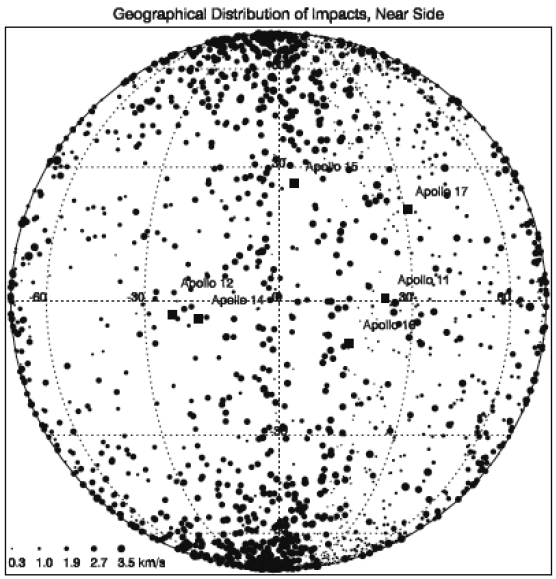


Fig. 3 The near side geological distribution of impact sites. The highest density of impacts is at both poles, which also correspond to the largest impact velocities

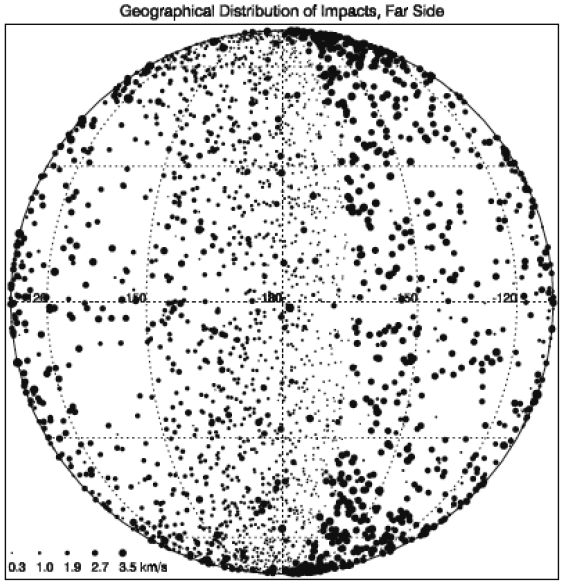


Fig. 4 The far side geographical distribution of impact sites. The far side contains the most number of impacts with vertical impact speeds below 1.0 km s^{-1}

Mapped results from Armstrong 2010, showing accumulations of Earth transferred material. Polar emplacement occurs at higher velocities but densely distributed, while other regions have much lower impact velocities but still patchy areas of significant deposition.

What to Look For

Plausibility experiments:

Organics –
Bowden et al 2009, Parnell et al 2010,
Impact survival of hopanes, pregnanes, steranes, anthracene, phenanthrene, methylanthrene, n-alkanes and more.

Matthewman et al 2015, 2016 etc.
Heating survival *a la*' lava flows, promotes polymerization.

Microorganisms (bacteria in these cases) – *Burchell et al 2001, 2003, Horneck et al 2001, 2008, Fajardo-Cavazos et al 2009*
Some microbial survival even at highest velocity direct impacts.

Lichens – *Sanchez et al 2007*
Capsule summary, remain 100% viable in space conditions

Plant Seeds – *Jerling et al 2008, La Voci et al 2009*
Capsule summary – Organics survive impact shocks of 1 GPa or less, no viable seeds.

Animals – No one as of yet….Would tardigrade tuns (dense dormant stage) survive or at least be recognizable?

How Will Specimens Be Affected?

- On-Earth impact effects (*Melosh, 1988)*
- Moon impact effects (*e.g. Armstrong et al 2002, Crawford et al 2008)*
- Lunar UV, significant but it doesn't take much burial to protect it.
- Lunar ionizing radiation damage
  - Significant literature on this issue of how much solar and GCR flux there is
  - Extremely variable because of lunar latitudinal and topographical circumstances
- Lunar environmental thermal effects
  - Expansion & contraction spalling of exposed near surface emplacements
  - Earth experience in polar and high altitude regions.
  - Relatively easy to simulate in the lab, maybe???
- Crater erasure (e.g. *Hirabayashi et al 2017*)
  - Could be a destructive force on relatively surficial astrobiological material
  - Could be a protective mechanism burying astrobiological material
- **Synergistic destructive/protective interaction of all of the above factors**
- **How hard is it to be a "fossil" on the Moon?**

Solar & GCR Radiation Effects

- Majority of charged particles are ions from the Sun and only penetrate μs to mms in depth
- GCR high energy particles penetrate to meter-scale depths, produce daughter cascades & leave tracks (Vaniman et al. 1991 & others discussed in Rumpf et al 2013).

Thermal Effects of Transfer

- Typical impact speeds ~ few kms s^{-1}
- Worst case shock pressures at 5kms s^{-1} and vertical impact, ~20 GPa at leading edge, but ~10 GPa at trailing edge (Crawford et al 2008).
- Silicious preservation might hold up relatively well for small specimens???
- Carbonates have much lower thermal tolerance, ~400^{o}C

Heat Transfer from Overlying Lava Flows

Rumpf et al 2013

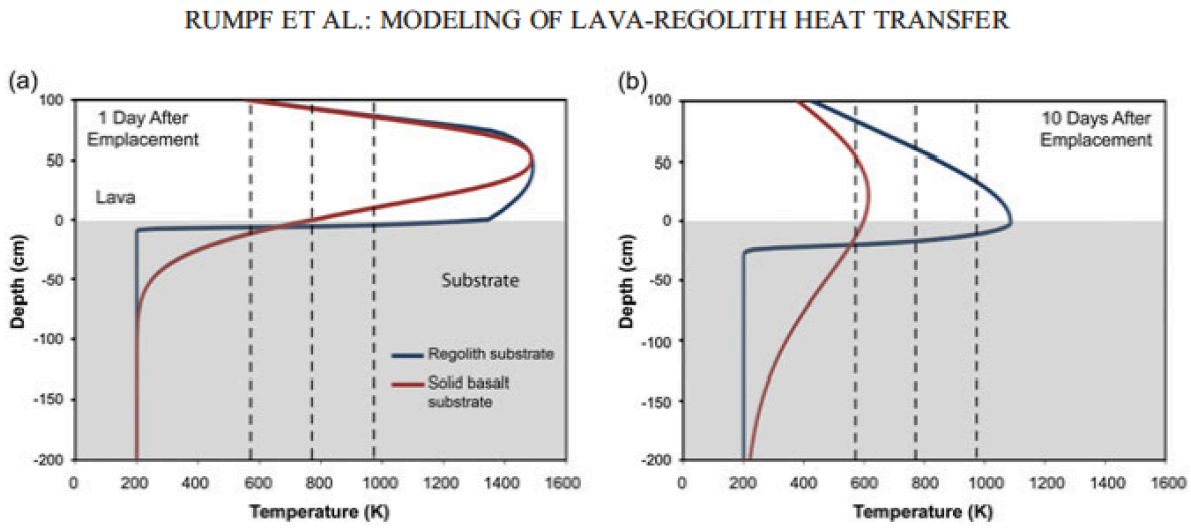


Figure 8. Temperature profiles through lava and regolith at (a) 1 and (b) 10 days for solid basalt (purple) and regolith (orange) substrates. Both cases include variable thermophysical properties and latent heat release. Initial lava and regolith temperatures are 1500 and 200 K, respectively. Vertical dashed lines indicate temperatures at which specific particles will begin to volatilize (Table 1).

Heat transfer from lava into basalt or regolith scale less than linearly, thus, a 10 m lava flow heat propagation goes only 9 times as far as a 1m flow (rather than 10 m).

However, flows were infrequent with inter-regnum regolith formation, ranging from several 100 million to more than a billion years duration (Hiesinger et al 2000, 2003).

Thus, we may find a nice stratigraphic sequence upon drilling, or the intervals are too lengthy to have provided much protection of entombed astrobiological materials.

TAKE-HOME MESSAGE:

- Lunar-residing, Earth-derived astrobiological materials are distinctly possible.
- Some very valuable work has been done on various aspects of the issue.
- A synthesis of these fragments plus additional germane information is timely.
- Sensitization of future lunar human and non-human expeditions to the prospects.

Where all the best *"future lunar fossils"* hang out!

Fly Me To The Moon Saloon, Telluride Colorado